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ESTIMATE OF THE AERODYNAMIC ROUGHNESS PARAMETERS OVER AN INCOMPLETE CANOPY COVER OF COTTON

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ABSTRACT

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Wind speed and temperature data at five levels were used to estimate the roughness length, z_{om}, and displacement height, d_o, for a sparsely covered cotton field with an average plant height of 32 cm and 1-m width furrows ~16 cm in depth. Five near-neutral cases produced an estimate of $z_{om} = 0.066$ m (± 0.043) and $d_o = 0.31$ m (± 0.20). In terms of obstacle height, h (i.e., furrows and plants), this yields $z_{om}/h \simeq 0.14$ and $d_o/h \simeq 0.65$. Confidence in the estimates of the roughness parameters was obtained with a comparison of the sensible heat flux, H, determined by K-theory relationships for gradients of wind speed and temperature in the surface layer and by measurements using the eddy correlation technique. The root mean square error was ~30 W m^{-2} between the two methods.

INTRODUCTION

One of the uses of remote sensing data is to determine the energy balance at the earth's surface. One such approach employs surface temperature, T_s, determined by remote sensing observations in the visible and thermal infrared region. For a review of the development of this method see Jackson (1985).

This approach works well under full canopy conditions or when foliage temperatures are determined (Hatfield et al., 1983; Seguin, 1984; Reginato et al., 1985), but difficulties arise when T_s is a composite of soil and vegetation temperatures, as in the case of airborne thermometric observations over sparse or

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incomplete canopy cover (Kustas et al., 1987). Kustas et al. (1988) found that the bulk transfer equation for sensible heat flux, H (Choudhury et al., 1986), written as a resistance expression (see eq. 2) does not yield satisfactory estimates of the surface energy balance when compared to values given by the Bowen ratio technique. Unfortunately, there were no wind profile data available from the experimental site to obtain reliable estimates of the momentum roughness parameters which are important in the determination of the resistance to heat transfer.

Since a considerable amount of the earth's land surface does not contain full canopy cover, it is of paramount importance to understand and develop relationships between remote sensing information on T_s, the amount of vegetation and the resistance to heat transfer. To have a better understanding of these relationships, this paper is concerned with the estimation of the momentum roughness length, z_{0m}, and displacement height, d_0, for an incomplete canopy cover of cotton. With an estimate of d_0, sensible heat fluxes are also calculated using K-theory relationships for wind and temperature and compared to eddy correlation data.

SITE AND INSTRUMENTATION

Profiles of wind speed and temperature above a cotton field located in Maricopa Farms, Arizona, were collected from approximately noon (local time) starting 10 June 1987 Day of Year (DOY) 161 and ending in the early afternoon on 14 June 1987, DOY 165. The field was designated as Number 28 and had a rectangular dimension of $\sim 300 \times 1600$ m with the rows orientated north–south. The adjacent field north contained plowed wheat stubble, while the adjoining fields south and east were bare soil. To the west, was a pecan plantation. The topography within several kilometers of the farm is flat with an average elevation of ~ 360 m above mean sea level and an average surface pressure of ~ 950 mb (L. Hipps, personal communication, 1987).

Row spacing in Field 28 was 1-m width furrows ~ 16.5 cm deep. The average height of the cotton plants was 32.3 cm (± 4 cm). Figure 1 is a cross-section of a furrow and cotton plant row illustrating various dimensions. From photographs taken at nadir, canopy cover was between 20 and 25% (P. Pinter, personal communication, 1987).

Profiles of wind speed and temperature were determined at five levels above the surface. The levels were 1.2, 1.4, 1.8, 2.4 and 3.0 m above the furrows. One mast contained both the temperature and wind sensors, and was situated near the middle of the field. This allowed a fetch for easterly and westerly winds of ~ 800 m. Northerly and southerly winds had fetches of ~ 150 m. The direction of the arms supporting the anemometers alternated between north and south, while the temperature sensors faced west. This allowed minimum sensor obstruction for easterly and westerly wind directions.

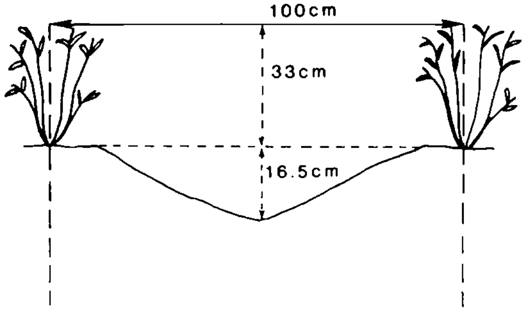

Fig. 1. Cross-section of furrow and row crop with dimensions (scale 1:10).

Half-hourly estimates of wind speeds, u, and air temperatures, T_a, were obtained for DOY 161 and switched to 20-min averages in the early morning of DOY 162. Wind speed and air temperature values were recorded every second; thus the average for 30- and 20-min periods consisted of 1800 and 1200 samples, respectively. The three-cup anemometers were R.M. Young D-C generated with a threshold velocity of ~ 40 cm s^{-1}. The temperature sensors were fine wire copper constantan thermocouples designed by Thomas Clarke of the U.S. Water Conservation Laboratory, Phoenix, AZ. All data were recorded on a Campbell* Scientific 21X datalogger. Sensible heat flux was measured using the eddy correlation technique. Vertical wind and temperature fluctuations were measured with a sonic anemometer and fine wire thermocouple, respectively, and were sampled at 10 Hz. The sonic system was located southeast of the profile instrumentation at a height of 2.4 m above the furrows. The position and height of the sensors allowed adequate fetch for westerly winds of the order of 1 km, but inappropriate fetch conditions (i.e., of the order of 100 m) for northerly or southerly winds. The upwind fetch to the east was ~ 400 m, which is marginal. Data recording was performed by a Campbell* Scientific 21$\times$ datalogger.

THEORY

If there are several levels of temperature and wind speed observations above a surface, an approach similar to Thom et al. (1975) can be used to determine the sensible heat flux, H. With gradients of wind speed and air temperature, a relationship for computing H is derived by using the assumption that the eddy diffusivities of momentum and heat are identical when stability is close to neutral

*Trade names and company are given for the benefit of the reader and do not imply any endorsement of the product or company by the U.S. Department of Agriculture.

$$H = \rho C_p k^2 (\bar{z} - d_o)^2 \frac{\partial u}{\partial z} \frac{\partial \theta}{\partial z} / \Phi_h \Phi_m \tag{1}$$

where θ is the potential temperature (K), ρC_p is the volumetric heat capacity of the air (J m^{-3} K^{-1}), k (~ 0.4) is von Karman's constant, d_o is the displacement height and z is the geometric mean height between the levels used to calculate the gradients. The symbols Φ_h and Φ_m represent the gradient stability functions for heat and momentum, respectively.

In remote sensing applications where the surface temperature, T_s, is used to determine the surface energy balance, a bulk transfer equation for sensible heat is usually employed. It is typically written as an analogue to Ohm's law

$$H = (T_s - T_a) \rho C_p / r_{ah} \tag{2}$$

where r_{ah} (s m^{-1}) is the resistance to heat transfer. This resistance can be expressed in terms of classical surface layer similarity theory (Monteith, 1973; Brutsaert, 1982)

$$r_{ah} = \{\ln[(z - d_o)/z_{oh}] - \psi_{sh}\}\{\ln[(z - d_o)/z_{om}] - \psi_{sm}\}/k^2 u \tag{3}$$

where z_{om} and z_{oh} are roughness lengths for momentum and heat, respectively, ψ_{sh} and ψ_{sm} are the integrated forms of Φ_h and Φ_m, and z is the height where u and T_a are measured. Equation 3 requires the estimation of several length parameters which have various degrees of difficulty in their determination. For this report, discussion will center around the determination of z_{om} and d_o.

In a region close to the earth's surface (but some distance above the roughness obstacles) that is homogeneous, under a steady-state and under adiabatic (i.e., neutral) conditions, the wind profile is generally accepted to be logarithmic

$$u = \frac{u_*}{k} \ln[(z - d_o)/z_{om}] \tag{4}$$

where $u_* = (\tau_0/\rho)^{1/2}$ is the friction velocity, τ_0 is the surface shear stress and ρ is the air density. Probably, the most widely used approach employs a minimum of four levels of wind measurements to mathematically solve for d_o and z_{om} in eq. 4 by minimization of square errors (Robinson, 1962; Stearns, 1970).

Following the development of Robinson (1962), eq. 4 is rewritten to represent the sum of the squares of errors to be minimized

$$E = \sum_{i=1}^{n} \left[u_i - \frac{u_*}{k} \ln\left((z_i - d_o)/z_{om} \right) \right]^2 \tag{5}$$

where the subscript i stands for the i-th level of wind speed. Equation 5 is then differentiated with respect to u_*, d_o and z_{om}, and equated to zero. With some manipulation, an expression emerges which is an implicit equation for the unknown, d_o (Robinson, 1962; Covey, 1963). This expression is essentially a linear function of d_o which can be solved numerically by simple bisection to within ± 1 mm of the solution. Standard errors of the calculated values of d_o, z_{om} and u_* are obtained by assigning the measurement errors to the wind speeds. Consequently, the standard errors are estimated as functions of the data (Covey, 1963).

PAST WORK ON THE ESTIMATION OF z_{om} AND d_o

Reasonable estimates of z_{om} and d_o for vegetation have been obtained by using several empirical relationships as long as the surface is uniformly covered and fairly flat. The simple relationships of $d_o \sim \frac{2}{3}h$ and similarly $z_{om} \sim 0.13$ h have been considered reasonable approximations (Monteith, 1973; Brutsaert, 1982). However, both d_o and z_{om} for vegetation have been shown to be a function of u (Deacon, 1957; Maki, 1969). This suggests that the flexibility of plant stems and petioles and general leaf structure are factors that contribute to the deviation of d_o and z_{om} from the simple expressions given above.

A further complication results when the surface is not fully covered by vegetation. Then, the density of the vegetation becomes important as well as its shape. At present, the empirical equations for the estimation of z_{om} and d_o for incomplete canopy cover are probably plant specific (Verma and Barfield, 1979; Hatfield et al., 1985). Additionally, in the present study the furrows are of appreciable size to further complicate the situation. In other words, both the permeable–rough (i.e., the cotton plants) and the bluff–rough obstacles (i.e., the furrows) contribute to the momentum transport. Therefore, to obtain satisfactory estimates of z_{om} and d_o, they must be determined by more direct means, such as the wind profile method discussed above. But before such an approach can be used, data under near-neutral conditions must be found.

DETERMINATION OF NEAR-NEUTRAL CONDITIONS

With gradients of wind speed and temperature relatively close to the surface, stability can be estimated using a Richardson number, R_i

$$R_i = \frac{g}{T_a}\frac{\partial \theta}{\partial z} \Big/ \left(\frac{\partial u}{\partial z}\right)^2 \tag{6}$$

If temperature gradients, $\partial T_a/\partial z$, are measured close to the surface, they can replace $\partial\theta/\partial z$ in eq. 6 with little error in the estimate of R_i. Near-neutral conditions exist when $R_i \rightarrow 0$; this commonly occurs as a result of relatively small temperature gradients and large gradients in wind speed. To obtain profiles with reliable wind speeds that also were under near-neutral conditions, R_i estimated for levels 1–2, 2–3, 3–4 and 4–5 all had to meet the criterion $|R_i| < 0.015$.

THE DATA

Figures 2 and 3 are plots of the 20- or 30-min average wind speed from all five measurement heights and R_i taken between levels 1 and 5 for each day. The plots of R_i illustrate its diurnal trend, while the plots of u indicate, roughly, time intervals where steady state conditions are likely to have existed. Non-steady conditions occur when there is appreciable gustiness caused by large eddies, associated with synoptic events, that penetrate the surface layer. These eddies only affect the horizontal transport processes (Monin, 1959) and consequently are not correlated with vertical transport of momentum locally. Thus, using wind data under non-steady conditions would result in erroneous values of d_0 and z_{0m}. Figure 4 illustrates the wind direction (hourly estimates) in degrees from north for each day. As mentioned earlier, winds generally from the east and west give a good fetch and flow roughly perpendicular to the rows of cotton. Southerly and northerly winds give a poor fetch and flow parallel to the rows. The use of winds parallel to the rows will result in significantly dif-

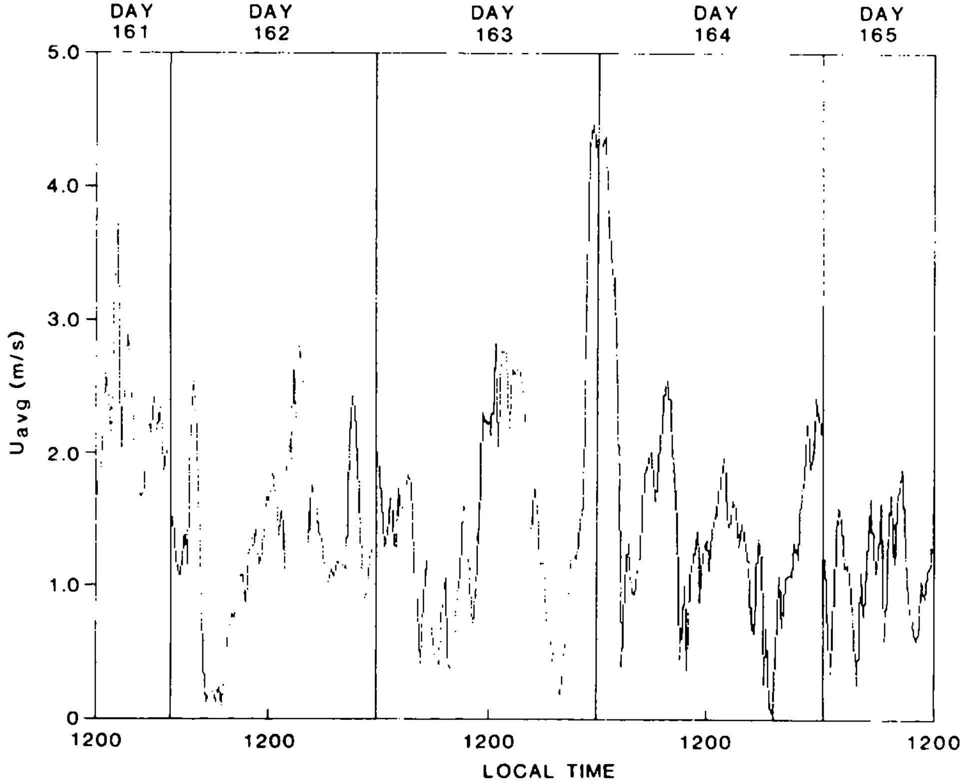

Fig. 2. Average wind speed, u_{avg}, calculated from all five anemometer levels.

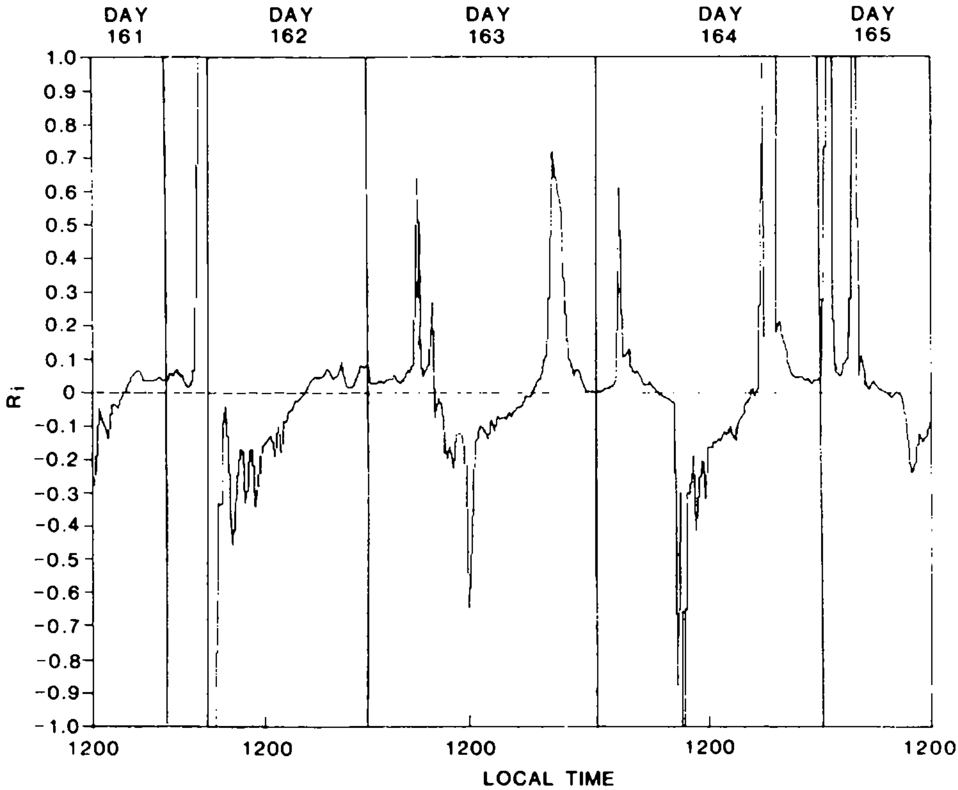

Fig. 3. Average Richardson number, R_i, calculated from levels 1 and 5.

ferent estimates of z_{om} and d_0. Thus, knowledge of wind direction is of paramount importance.

Table 1 gives the profile data for five near-neutral cases. Note that they occurred at night over consecutive 20-min intervals starting on DOY 163 at 2320 h and had comparable wind speeds and direction. This provides some confidence that the wind data were probably observed under steady conditions with a good fetch and a transverse flow to the obstacles. Table 1 also lists R_i between each level and the corresponding average R_i. The average R_i gives a stability correction on the order of 0.05 (Panofsky and Dutton, 1984). This, for all practical purposes, is negligible.

RESULTS AND DISCUSSION

The procedure briefly outlined above is employed for the five near-neutral profiles and the results are shown in Table 2. Note the relatively large standard errors in d_0 and z_{om}, which is not unusual when the profile method is used (Stearns, 1970). The wind data for the DOY 164, 0040 h give significantly

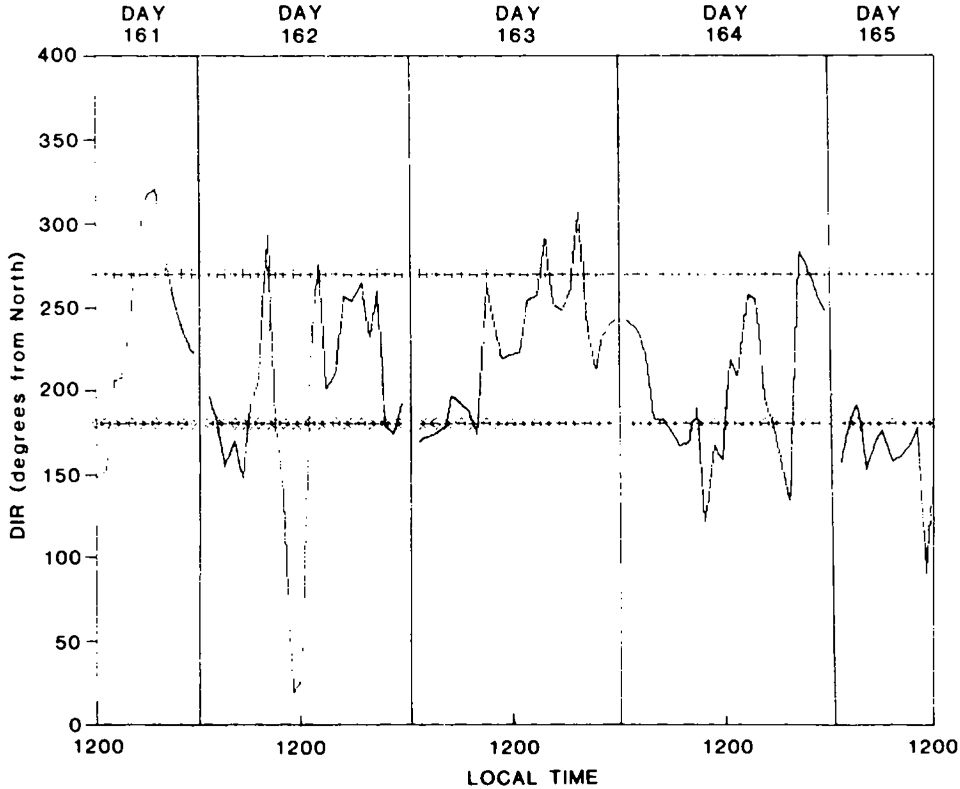

Fig. 4. Hourly averaged wind direction in degrees from north where ◇ represents a south wind and + indicates a west wind.

TABLE 1

Profile data for the five near-neutral cases

DOY (Julian Day)	Time (local)	u_1^a 1.2	u_2 1.4	u_3 1.8	u_4 2.4	u_5 3.0	R_{i12}^b	R_{i23}	R_{i34}	R_{i45}	R_{iAVG}^c	Wind direction (degrees from North)
163	2320	3.43	3.73	4.08	4.55	4.84	0.005	0.010	0.011	0.008	0.0085	237
163	2340	3.54	3.88	4.22	4.75	5.02	0.004	0.011	0.007	0.007	0.007	246
163	2400	3.39	3.64	4.03	4.47	4.74	0.007	0.008	0.012	0.010	0.009	252
164	0020	3.46	3.70	4.10	4.59	4.86	0.008	0.008	0.008	0.014	0.0095	242
164	0040	3.53	3.75	4.17	4.61	4.97	0.009	0.006	0.011	0.008	0.0085	235

[a] Subscript represents the level of wind speed. [b] Subscript represents the levels used to determine the Richardson number. [c] Average R_i calculated from the mean of all four values.

different values of d_o and z_{om} from the other four profiles, even though the wind direction for this particular 20-min interval is similar to the other profiles (see Table 1). Albeit this result points to some of the problems implicit in the

TABLE 2

Estimates of d_o, z_{om} and u_* and their standard errors with the five near-neutral cases

DOY (Julian Day)	Time (local)	z_{om} (m)	d_o (m)	u_* (m s^{-1})	Standard error z_{om} (m)	Standard error u_* (m s^{-1})	Standard error d_o (m)
163	2320	0.043	0.41	0.47	0.020	0.06	0.17
163	2340	0.040	0.45	0.48	0.038	0.10	0.27
163	2400	0.040	0.42	0.46	0.013	0.03	0.10
164	0020	0.065	0.30	0.52	0.040	0.08	0.22
164	0040	0.14	~0	0.65	0.035	0.04	0.13

profile method (Bradley and Finnigan, 1973), on the whole it is still deemed a reliable technique for estimating d_o and z_{om} (e.g., Jacobs and Schols, 1986). The significance of using d_o estimated with all five near-neutral cases and d_o determined without the seemingly spurious value ($d_o = 0$) as its pertains to the flux–gradient relationship for sensible heat will be discussed below. Figure 5 is a plot of all five profiles on a logarithmic scale.

From Table 2, the average d_o is ~0.31 m (± 0.20) and z_{om} is ~0.066 m (± 0.043). In terms of the height of the obstacles, h (i.e., the furrows plus cotton plants), this yields $z_{om}/h \simeq 0.14$ and $d_o/h \simeq 0.65$. These values are close to the simplified ratios used for vegetation under complete canopy cover (Monteith, 1973). To the authors' knowledge, the only other study with an incomplete canopy of cotton (Hatfield et al., 1985) found roughness parameters from a field with plants 50 cm in height and a 50% cover to be $z_{om} \simeq 0.24$ m and $d_o \simeq 0.2$ m. They had furrows of similar size and spacing (Hatfield, personal communication, 1987); thus $h \simeq 0.67$ m yields $z_{om}/h \simeq 0.36$ and $d_o/h \simeq 0.30$. A comparison with the present results shows that the ratio for z_{om}/h is ~2.5 times larger for Hatfield et al., while d_o/h is about twice as small. An increase in z_{om}/h with density of the roughness obstacles agrees with previous laboratory studies (Seginer, 1974; Raupach et al., 1980), as long as the density of the obstacles is not too large. The ratio d_o/h should also follow this trend, but in fact goes in the opposite direction.

The definition of d_o as the mean level of momentum absorption (Thom, 1971; Raupach and Thom, 1981) has been shown to be implicit in the usual derivation of the logarithmic law for momentum transport by mean wind using asymptotic matching arguments (Jackson, 1981). This definition of d_o implies that relative to h, the present study has a mean level of momentum absorption significantly higher than Hatfield et al. (1985). This difference may be partly caused by roughness sublayer effects (Garratt, 1980; Raupach et al., 1980) not accounted for by Hatfield et al. (1985). However, the relatively large standard errors in d_o (see Table 2) inhibit any further analysis into factors causing the

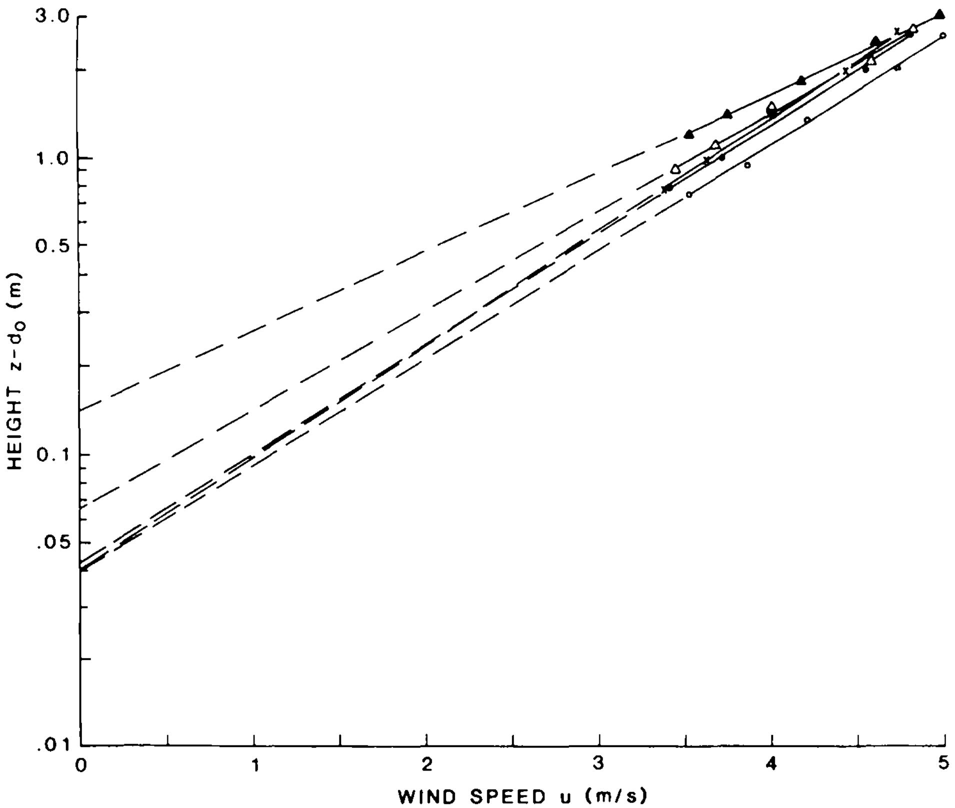

Fig. 5. Semi-logarithmic plot of the five neutral cases with their respective estimates of d_0 and z_{0m}.

disagreement. Only with more careful observations can this problem be adequately addressed.

As a means of checking the present estimates of d_0, eq. 1 was used to estimate values of H. These were compared to the measured values from the eddy correlation system. The only unknowns in eq. 1 were Φ_h and Φ_m. For unstable conditions, the empirical equations of Dyer and Hicks (1970) were employed (see also Brutsaert, 1982; Panofsky and Dutton, 1984)

$$\Phi_h = \Phi_m{}^2 = (1 - 16\,R_i)^{-1/2} \qquad (8)$$

For moderately stable conditions, the expression by Webb (1970) was used (see also Hicks, 1976)

$$\Phi_h = \Phi_m = (1 - 5.2\,R_i)^{-1} \qquad (9)$$

Gradients of wind speed and temperature measured over 1 m or less are relatively small. Consequently, the most consistent estimate of the gradients, with the profile instrumentation used in this experiment, came from using the values of u and T_a at levels 1 and 5; this yielded an estimate of the sensible heat flux, H_{15}, at a mean height, $\bar{z}$, of 2.1 m. Another estimate of sensible heat flux was an average value, H_{avg}, determined with gradients between levels 2 and 4 ($\bar{z}=1.9$) and levels 3 and 5 ($\bar{z}=2.4$ m). The main objective of the comparison between H_{avg} and H_{15} was to reveal any bias in the values of H_{15} caused by the lowest level of u and T_a being inside the roughness sublayer. For all days, only data where the velocity at the lowest level was >1 m s^{-1} or roughly twice the stall speed of the anemometers and monotonically increasing or decreasing temperature profiles were used. The latter requirement eliminated profile data in the early morning and late afternoon when the boundary layer was in transition between stable and unstable conditions. The requirement of relatively high wind speeds eliminated profile data that would be affected by the stall speed of the anemometers. It also helped in disposing of data affected by periods of unsteadiness because significant variations in u from hour to hour typically occurred under relatively low wind speeds. A total of 87 wind and temperature profiles (close to 1/3 of the data) satisfied both criteria.

Figure 6 is a plot of H_{eddy} versus H_{15} and H_{avg}. There is a fair amount of scatter because the requirements for adequate fetch and winds traversing the row crop were not considered. Linear regression results given in Table 3 show that both H_{avg} and H_{15} have a root mean square error ($RMSE$) of ~ 35 W m^{-2} and a slope <1 by $\sim 20\%$.

A slope <1 suggests that the profile method generally estimates a larger

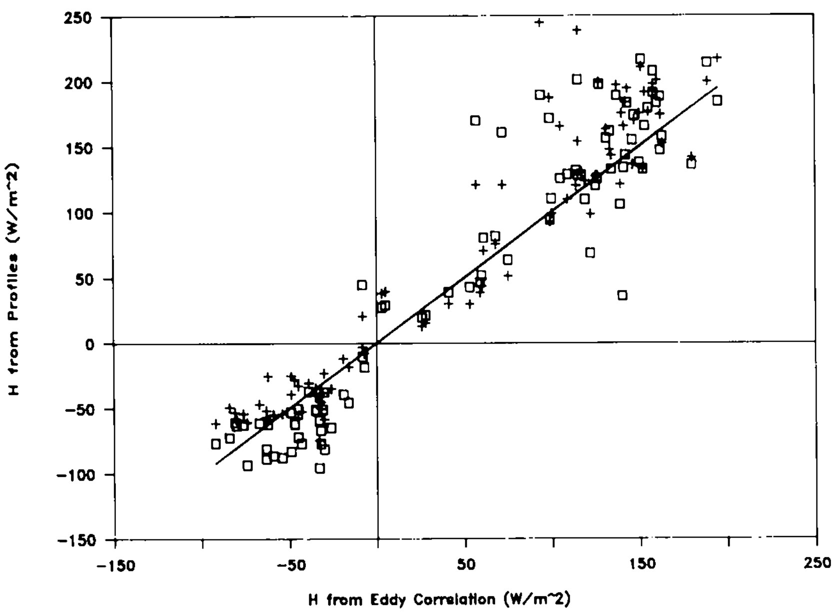

Fig. 6. Comparison of H_{15} (□), and H_{avg} (+) vs. H_{eddy}. The solid line represents perfect agreement with H_{eddy}.

TABLE 3

Regression results with $d_o = 0.3$ m (87 observations)

	H_{eddy} vs. $H_{1.5}$	H_{eddy} vs. H_{avg}
R^2 (coefficient of determination)	0.89	0.90
Regression equation	$8 + 0.80\ H_{1.5}$	$-4 + 0.84\ H_{avg}$
Standard error of H_{eddy} estimate (W m^{-2})	29	27
Standard error of coefficient	0.03	0.03
RMSE (root mean square error) (W m^{-2}) $\left[\sum_{i=1}^{n} (H_{eddy} - H_{1.5(avg)})^2/n\right]^{1/2}$	36	35

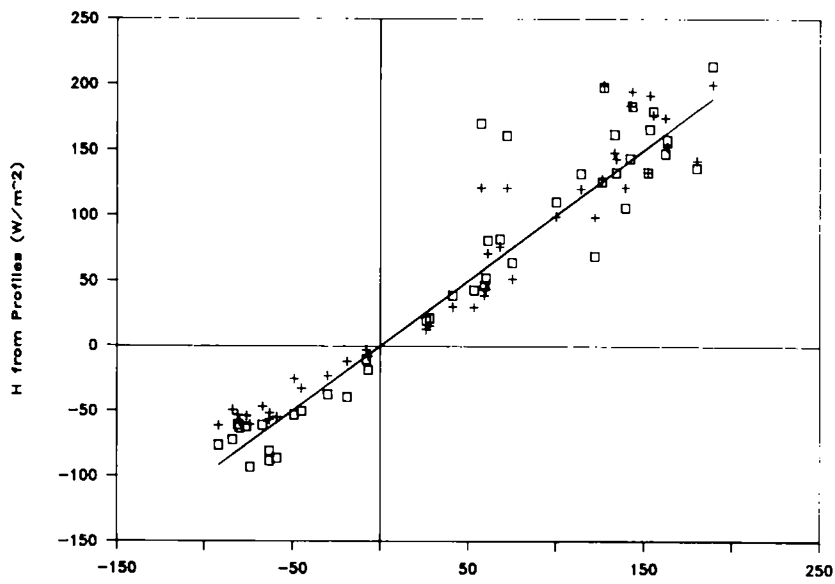

Fig. 7. As Fig. 6, except that observations have adequate fetch (44 observations).

sensible heat flux compared to the eddy correlation system. This discrepancy is, in part, the result of frequency band limitations with the eddy correlation technique, which leads to an underestimation of the turbulent fluxes typically on the order of 5–10% (Moore, 1986). Another reason is the influence on the statistics from data with inappropriate wind directions (i.e., north–south winds) leading to poor fetch conditions and requiring a different d_o in eq. (1).

To reduce the scatter in Fig. 6, only data where the wind direction (*WD*) was between northwest and southwest (i.e., $225° < WD < 315°$) were considered. This criterion provided optimal fetch conditions for the profile and eddy correlation systems; however, it reduced the data set by about 1/2 to 44 values

TABLE 4

Regression results with $d_o = 0.3$ m and appropriate upwind fetch (44 observations)

	H_{eddy} vs. H_{15}	H_{eddy} vs. H_{avg}	H_{15} vs. H_{avg}
R^2 (coefficient of determination)	0.90	0.93	0.97
Regression equation	$2+0.88\ H_{15}$	$-8+0.96\ H_{avg}$	$-9+1.07\ H_{avg}$
Standard error of H_{eddy} estimate (W m^{-2})	29	24	18[a]
Standard error of coefficient	0.04	0.04	0.03
RMSE (root mean square error) (W m^{-2})	31	26	20

[a]Standard error of the H_{15} estimate.

TABLE 5

Regression results with $d_o = 0.4$ m and appropriate upwind fetch (44 observations)

	H_{eddy} vs. H_{15}	H_{eddy} vs. H_{avg}
R^2 (coefficient of determination)	0.90	0.93
Regression equation	$-2+0.97\ H_{15}$	$-8+1.07\ H_{avg}$
Standard error of H_{eddy} estimate (W m^{-2})	29	24
Standard error of coefficient	0.05	0.05
RMSE (root mean square error) (W m^{-2})	28	25

for the comparison. The scatter, as illustrated in Fig. 7, between H_{eddy} and the estimates with eq. 1 appears to have decreased substantially. Table 4 shows that the slopes are closer to 1 and there is a reduction in the *RMSE*. The statistics also suggest that the overall results with H_{avg} are better than with H_{15}. However, the magnitude of the slope and of the *RMSE* between H_{avg} and H_{15} in comparison to the results with H_{eddy} (see Table 4) implies that the differences between H_{avg} and H_{15} are within measurement errors.

If the estimate of $d_o \simeq 0$ in Table 2 is assumed to be spurious, the remaining four near-neutral cases yield a slightly larger value of d_o (i.e., ~ 0.4 m). With $d_o = 0.4$ m, there is little improvement in the prediction of H_{eddy} by eq. 1 with the reduced data set (i.e., the 44 observations). Table 5 shows a slight decrease in the *RMSE* and an increase in the slopes of $\sim 10\%$ from the values in Table 4. Therefore, it appears that a larger d_o is probably unwarranted because of the minimal reduction in the *RMSE*.

CONCLUDING REMARKS

There is a general dearth in research efforts concerned with the determination of the roughness parameters, z_{om} and d_o, over partial canopy cover. However, if remotely sensed surface temperature is to be used for computing the transfer of sensible heat flux to or from a partially vegetated surface, it is of paramount importance to have reliable estimates of d_o and z_{om}. In the early stages of growth of many agricultural crops, the existence of furrows as well as plant spacing will affect the turbulent transport of heat, water vapor and momentum. The influence of the furrows on the magnitude of the roughness parameters will depend upon plant and furrow dimensions (i.e., height, width and spacing) as a minimum. Wind direction, as a function of row orientation, must also be considered because z_{om} and d_o will differ depending on whether the flow is generally across or along the rows.

The results of the present study suggest that the furrows contributed significantly to the magnitudes of the roughness parameters. This is easily seen by comparing the magnitudes of d_o (~ 0.3 m) with the height of the vegetation (i.e., ~ 0.3 m); they are equal only because of the furrows. If the furrows were not present, then previous studies would suggest that d_o would be at most 2/3 of the vegetation height (see Brutsaert, 1982). The values of z_{om}/h and d_o/h are only applicable for the given vegetative and furrow dimensions in the present study, and only for winds traversing the rows. Unfortunately, inadequate fetch conditions for north–south winds prevented any estimates of the roughness parameters for flow parallel to the obstacles.

Clearly, more studies are necessary to quantify the relationships between row crop dimensions and the roughness parameters. In particular, it would be extremely useful to consider how z_{om}/h and d_o/h vary throughout a growing season and their dependence upon wind direction with regard to row orientation.

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